



# Testing lepton flavour and lepton number violation at ATLAS

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on behalf of ATLAS Collaboration

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December 14<sup>th</sup>-16<sup>th</sup>, 2009

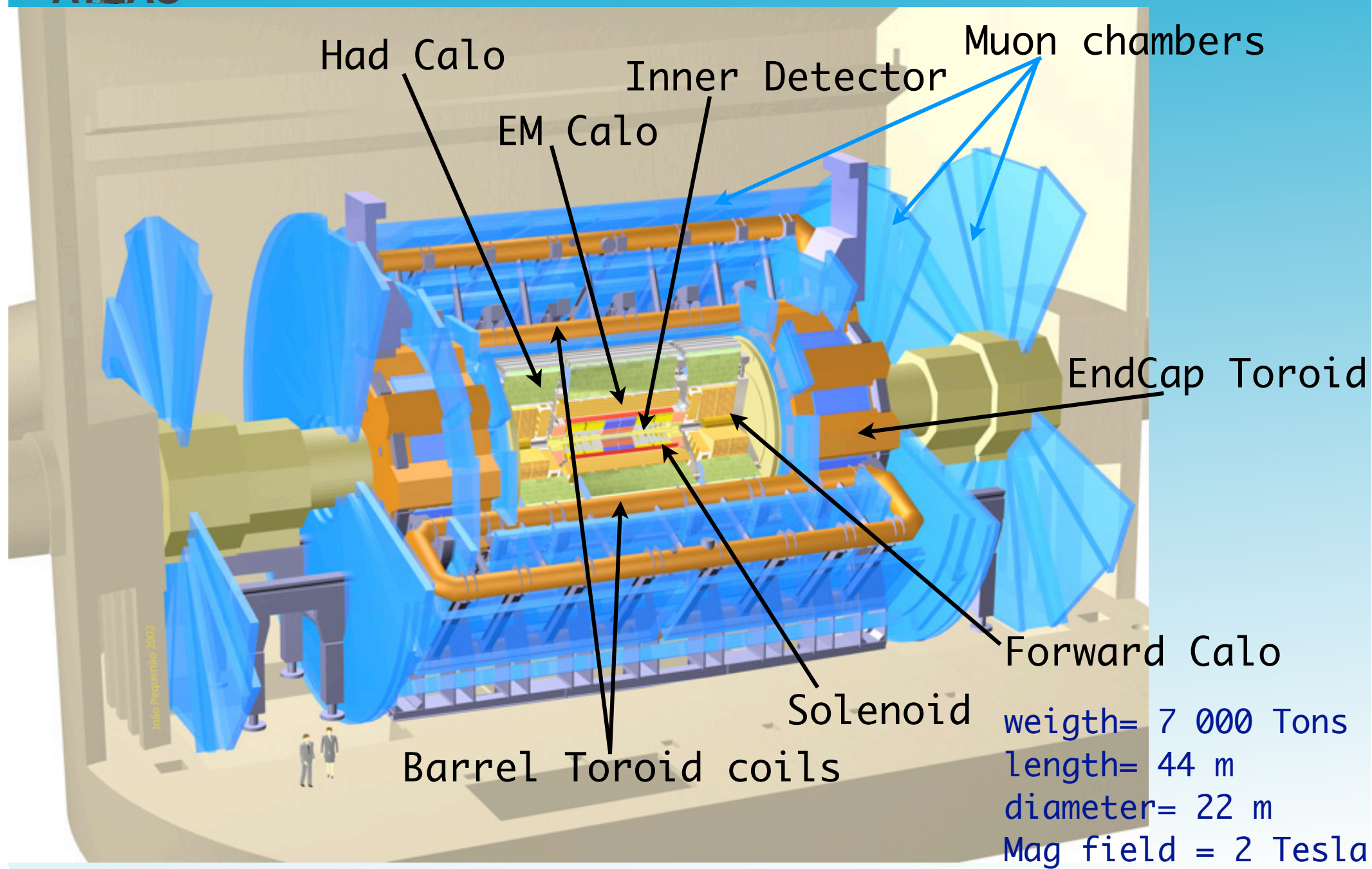
- ATLAS - generalities
- LHC time table - what we expect
- Motivations for LFV / LNF
- Possible channels & previous studies
  - $\tau \rightarrow \mu \gamma$
  - SuSY & SUGRA models
  - 2HDM model
  - Double Charged Higgs
  - LR symmetric models
- Outlook



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# Detector Overview

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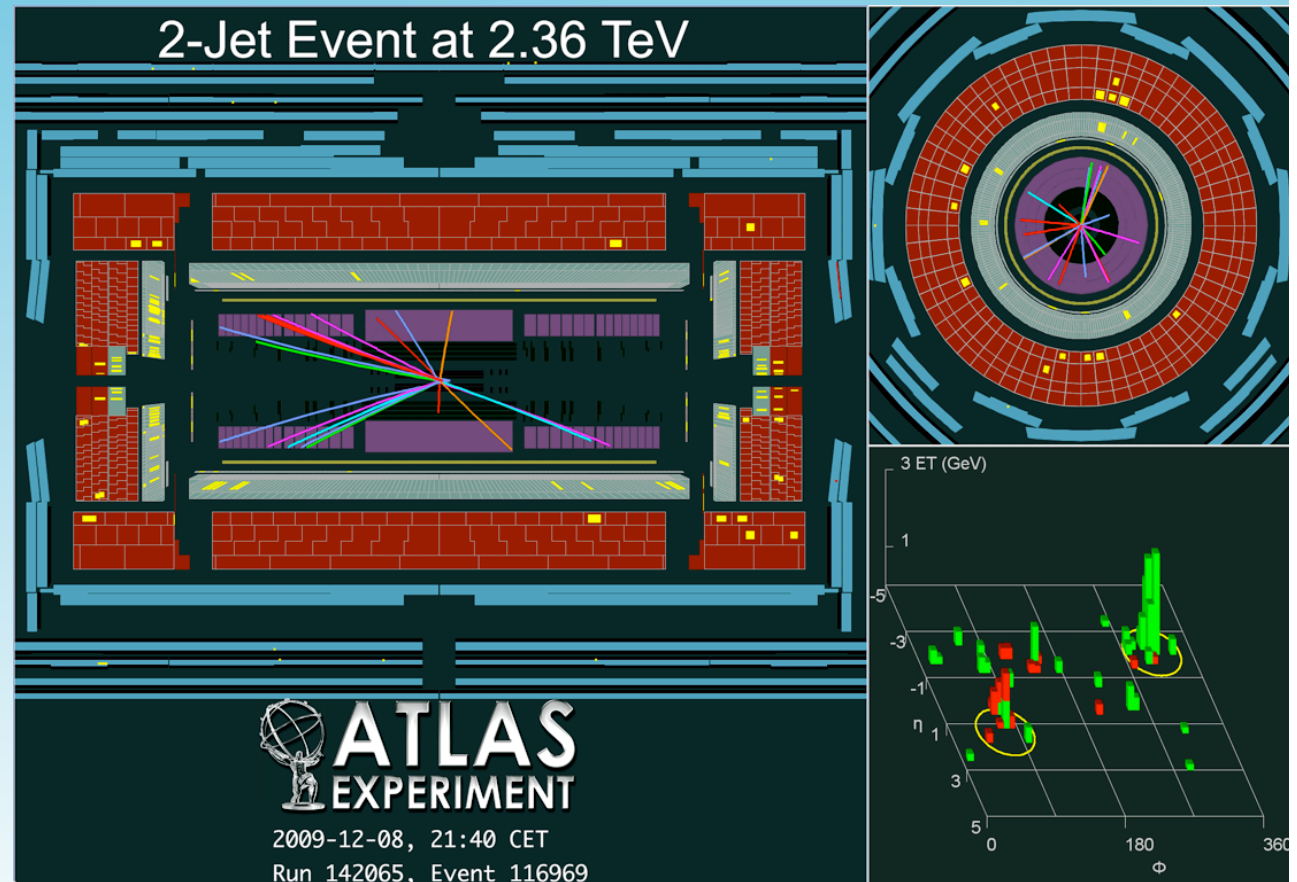




# Experiment status

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- In most of 2009, ATLAS recorded cosmic rays which were used for calibration & alignment.
- ATLAS has started taking beam data
  - all sub-detectors are active, providing data
  - collisions  $\sqrt{s}=2.36\text{TeV}$  are recorded.
    - Display of a 2-jet candidate with uncalibrated ET of 23GeV & 16GeV and  $\eta$  of -2.1 & 1.4, respectively.
  - collisions with stable  $\sqrt{s}=900\text{GeV}$  are being recorded.







# LHC Schedule

- initial period:

- late 2009: first collisions @  $\sqrt{s} = 0.9$  TeV
- 2010 collisions @  $\sqrt{s} = 7$  TeV, later  $\sqrt{s} = 10$  TeV
- 2011 collisions @  $\sqrt{s} = 14$  TeV
- $\mathcal{L} = 1.2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , expect  $10 \text{ fb}^{-1} / \text{year}$ , = low luminosity

- nominal runs (after 2011):

- $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , expect  $100 \text{ fb}^{-1} / \text{year}$ , = nominal luminosity
- Ultimately,  $\mathcal{L} = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  (cryo limited)

- SLHC (after 2020?):

- $L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ , expect  $1000 \text{ fb}^{-1} / \text{year}$



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# LFV Motivations

- Atmospheric / Solar / Accelerator / Reactor experiments all favor Neutrino Oscillations

K2K, accelerator:

$$\nu_{\mu} \longrightarrow \nu_{\tau}$$

Kamland, Reactor:

$$\bar{\nu}_e \longrightarrow \nu_x$$

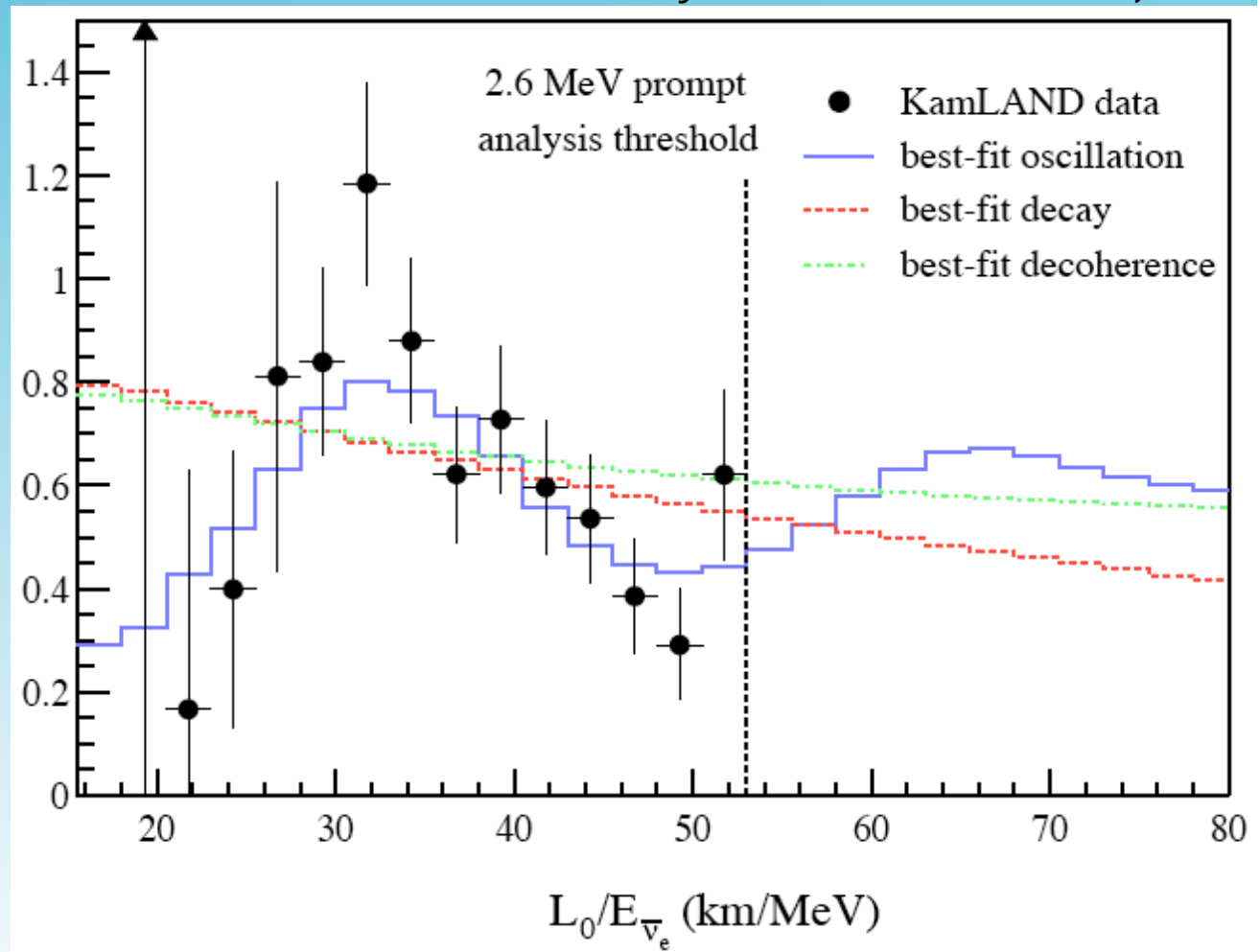
SK2, Atmospheric:

$$\nu_{\mu} \longrightarrow \nu_{\tau}$$

SNO, Solar:

$$\nu_e \longrightarrow \nu_x$$

Phys.Rev.Lett.94:081801,2005



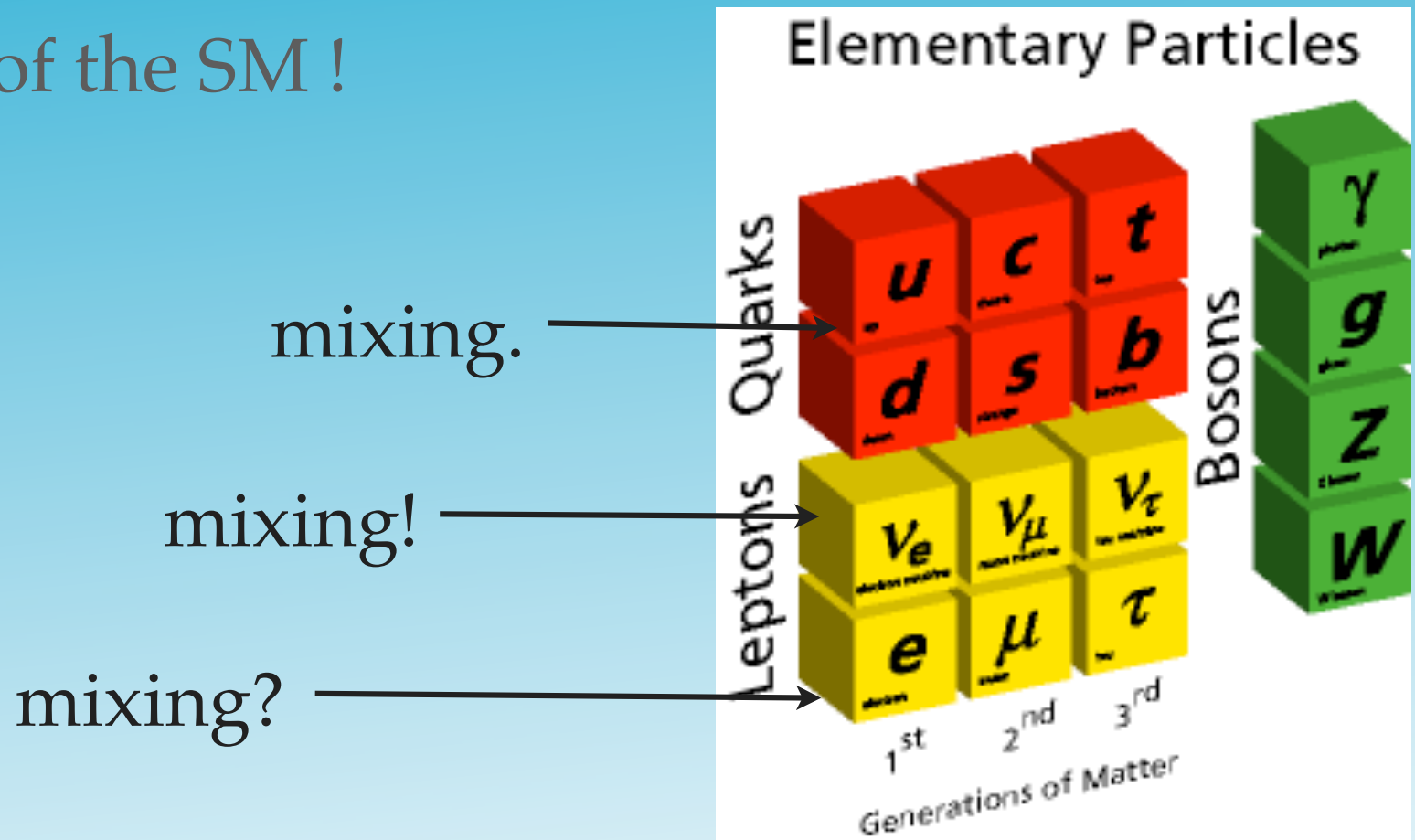


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# more motivations

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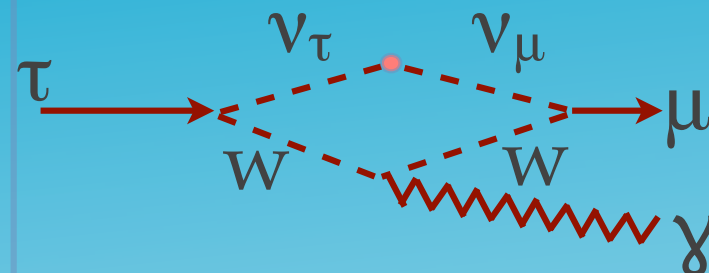
Lepton Flavor Conservation is not a true requirement of the SM !



The same for Lepton Number Conservation if charge conservation can be satisfied or for Majorana fermions.

# LFV diagrams

EW theory from  
neutrino oscillations:



BABAR collaboration

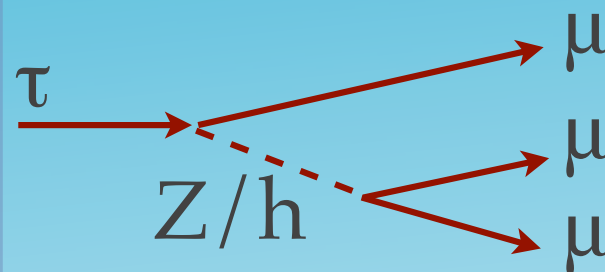
Phys. Rev. Lett. 95 (2005) 041802

BR ( $\tau^\pm \rightarrow \mu^\pm \gamma$ )  $< 6.8 \times 10^{-8}$  @ 90% CL

arXiv:0908.2381 (2009)

BR ( $\tau^\pm \rightarrow \mu^\pm \gamma$ )  $< 4.4 \times 10^{-8}$  @ 90% CL

if LFV exists, SM:

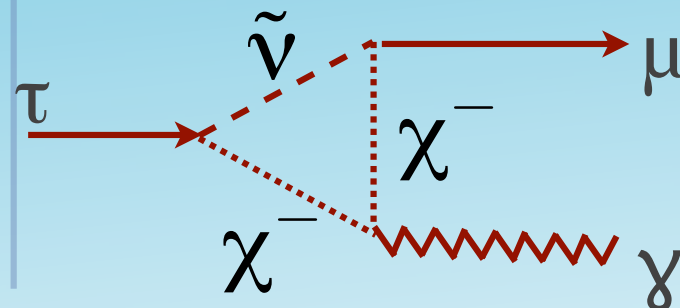


Belle Collaboration

arXiv:0708.3272, proceedings of lepton-photon 2007 & EPS 2007

BR( $\tau^\pm \rightarrow \mu^\mp \mu^\pm \mu^\pm$ )  $< 3.2 \times 10^{-8}$  @ 90% CL

if LFV and beyond  
SM exist:



PDG-04

$$\tau \rightarrow \mu \gamma < 1.1 \times 10^{-6}$$

$$\tau \rightarrow e \gamma < 2.7 \times 10^{-6}$$

$$\tau \rightarrow \mu \mu \mu < 1.9 \times 10^{-6}$$

$$Z \rightarrow e \mu < 1.7 \times 10^{-6}$$

$$Z \rightarrow \mu \tau < 1.2 \times 10^{-5}$$

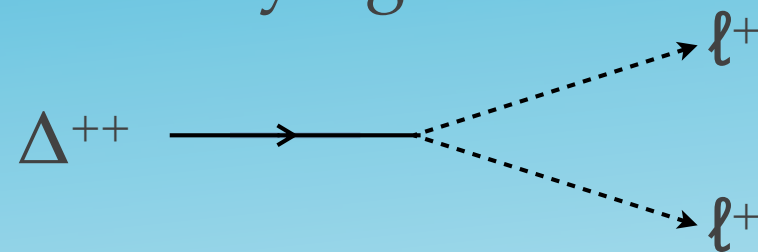
$$Z \rightarrow e \tau < 9.8 \times 10^{-6}$$



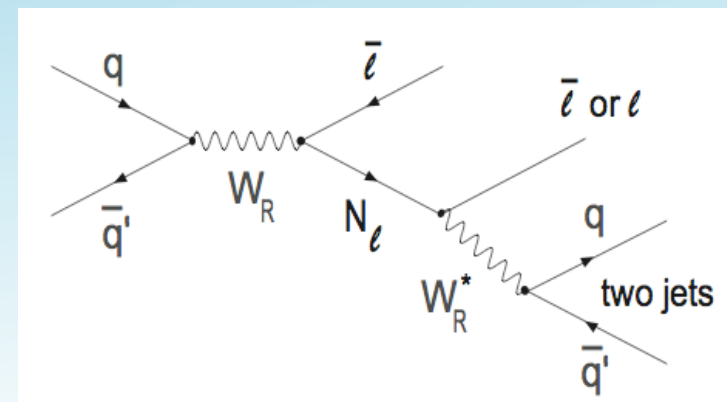


# LVN diagrams

- new particles could give rise to LVN
- e.g. doubly charged Higgs,  $\Delta^{++}$  decaying leptonically



- Majorana Neutrino (N) is its own anti-particle
- N decay gives LVN 50% of the time



# some signal channels

$$W \rightarrow \tau \nu_\tau$$

$$Z \rightarrow \tau \tau$$

$$B \rightarrow \tau \nu_\tau X$$

$\tau$  sources

- $\tau \rightarrow \mu \mu \mu$

- $\tau \rightarrow \mu \gamma$

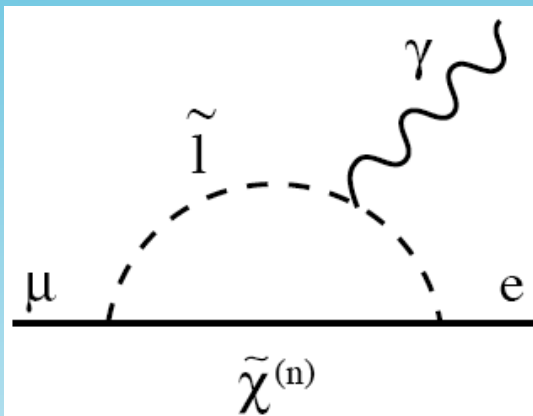
- $\chi_2 \rightarrow \chi_1 \tau \mu$

- $H/A \rightarrow \tau \mu$

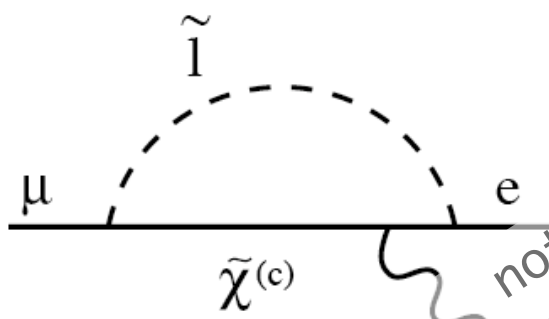
- $\mu \rightarrow e \gamma$

- $\mu \rightarrow e e e$

- $\tau \rightarrow e e e$



(a)



(b)

not feasible  
large  $e$  background/  
small mixing



$$\tau \rightarrow \mu \gamma$$

Source:  $q \bar{q} \rightarrow W \rightarrow \tau \nu_\tau$   
 $BR(\tau \rightarrow \mu \gamma) < 10^{-6}$

*generator cuts:*  $|\eta|_{(\gamma \& \mu)} < 2.5$   
 $6 \text{ GeV}/c < p_T(\mu)$   
 $20 \text{ GeV}/c < E_T(\gamma)$

*analysis cuts:*  $0.08 < \Delta R$   
 $6 \text{ GeV}/c < p_T(\mu) < 20 \text{ GeV}/c$

Background from FSR &  
 Radiative production:

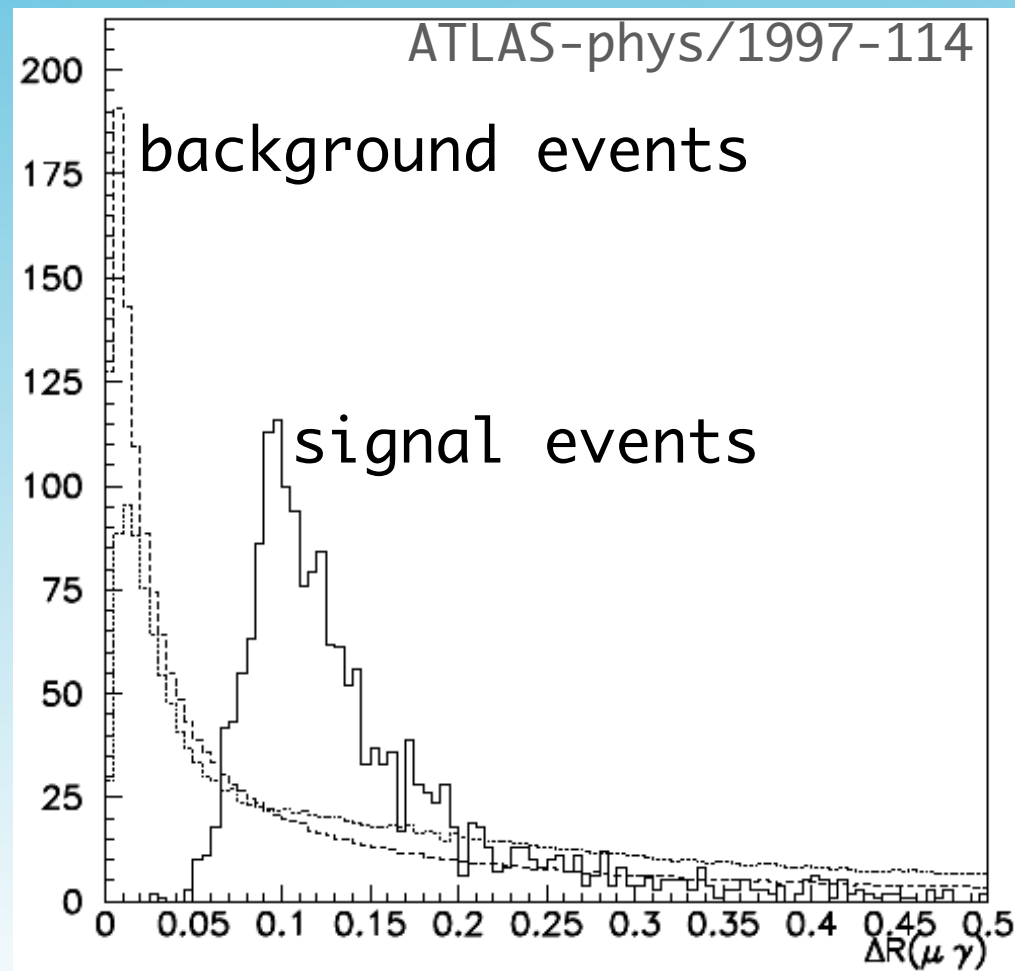
$$W \rightarrow \mu \nu_\mu + \gamma$$

$$W \rightarrow \tau \nu_\tau \rightarrow \mu \nu_\mu \nu_\tau + \gamma$$

*Pythia + Photos + Fast smearing was used.*

low luminosity

17 bg events/year for  $m_\tau$   
 <8 signal events/year





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# susy -1

Assume 6x6 slepton mass matrix :  $\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$

$$\begin{bmatrix} M_L^2 + D_L & 0 & 0 & 0 & 0 & 0 \\ 0 & M_L^2 + D_L & M_{\mu\tau}^2 & 0 & 0 & 0 \\ 0 & M_{\mu\tau}^2 & M_{\tau L}^2 + D_L & 0 & 0 & m_\tau \bar{A}_\tau \\ 0 & 0 & 0 & M_R^2 + D_R & 0 & 0 \\ 0 & 0 & 0 & 0 & M_R^2 + D_R & 0 \\ 0 & 0 & m_\tau \bar{A}_\tau & 0 & 0 & M_{\tau R}^2 + D_R \end{bmatrix}$$

LFV strength:  $\delta = \frac{M_{\tau\mu}^2}{M_L^2}$

LF breaking Term

Chirality breaking Term

Consider mSUGRA:

$m_0 = 100 \text{ GeV}$   
 $m_{1/2} = 300 \text{ GeV}$   
 $A_0 = 300 \text{ GeV}$   
 $\tan(\beta) = 10$   
 $\text{sgn } \mu = +$

if:  $\delta = 0$

$m_{\tilde{\chi}_1^0} = 122 \text{ GeV}$   
 $m_{\tilde{\chi}_2^0} = 228 \text{ GeV}$   
 $m_{\tilde{l}_L} = 232 \text{ GeV}$   
 $m_{\tilde{l}_R} = 156 \text{ GeV}$   
 $m_{\tilde{\tau}_1} = 145 \text{ GeV}$   
 $m_{\tilde{\tau}_2} = 233 \text{ GeV}$

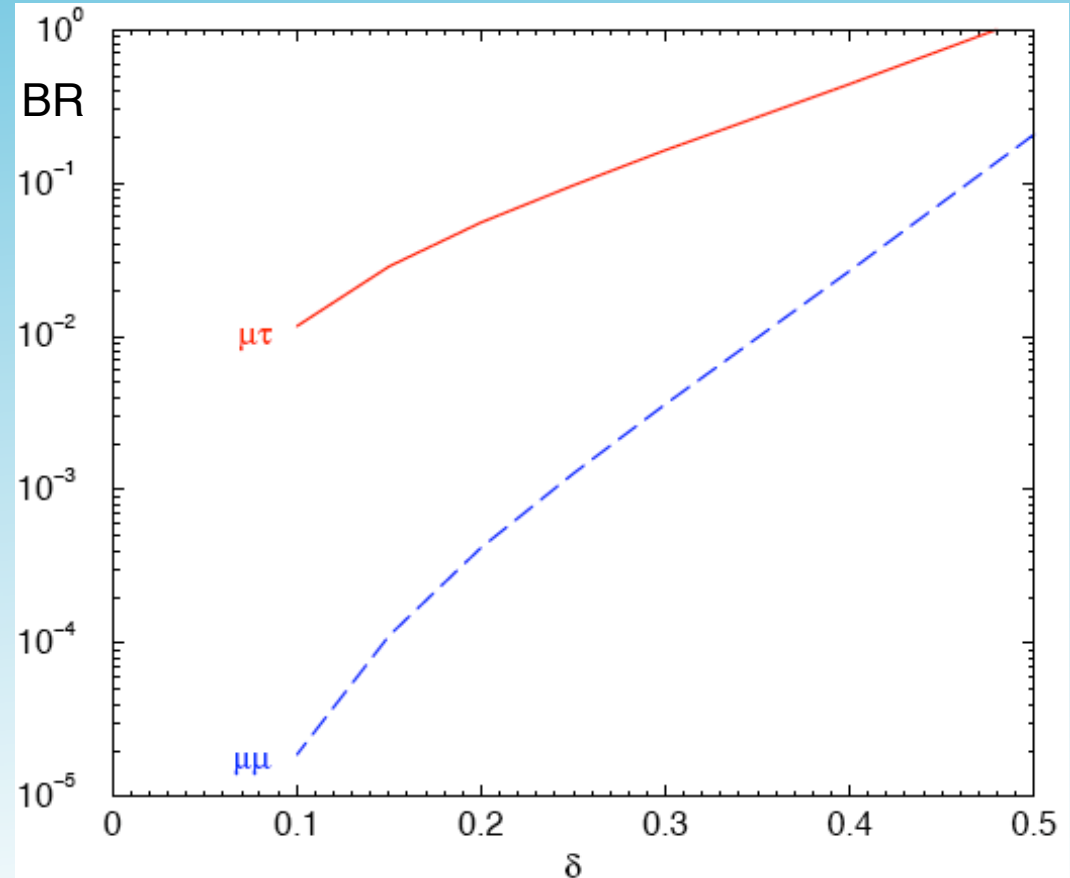
if:  $\delta \neq 0$   
 mixing

we have  $\tilde{\mu}$  in  $\tilde{\tau}_1$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \mu$$

$$\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$$

$$\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \mu$$





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# susy -2

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Phys. Rev. D 63, 115006 (2000)

Signal:  $E_{\text{miss}} \mu \tau_{\text{had}} j$

$$pp \rightarrow \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_2^0 q\tilde{\chi}_2^0$$

$$\rightarrow qq\mu\tau\tilde{\chi}_1^0 \mu\tau\tilde{\chi}_1^0$$

Selection cuts:

$$N_j \geq 4 \quad 1P_T > 100\text{GeV} \quad 3P_T > 50\text{GeV}$$

$$M_{\text{eff}} \equiv E_T^{\text{miss}} + \Sigma P_T > 800\text{GeV}$$

$$E_T^{\text{miss}} > 0.2M_{\text{eff}}$$

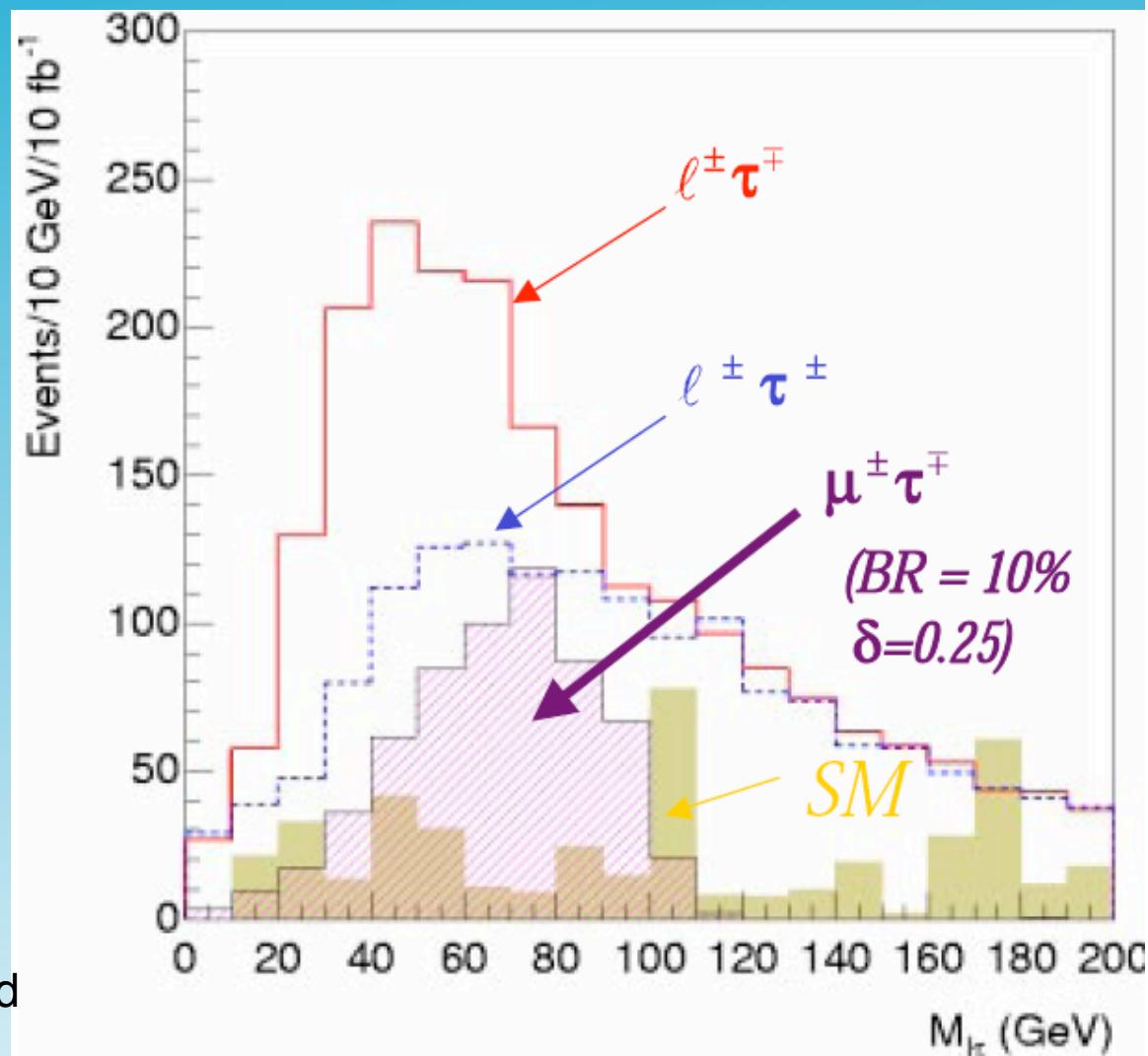
$$|\eta| < 2.5$$

$$R > 0.4$$

Backgrounds:

- SM background is very small
- Normal SuSY signal becomes background to LFV in SuSY

$$\tilde{\chi}_2^0 \rightarrow \tau\tau \quad \tilde{\chi}_1^0 \rightarrow \mu\tau \nu_\mu \nu_\tau \quad \tilde{\chi}_1^0$$



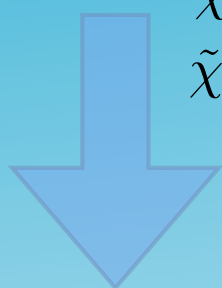
isajet +ATLAS fast simulation + realistic smearing  
+ full tau simulation @ low luminosity

- How can we extract the LFV events?



LFV gives harder mass distribution  
and more muons compared to  
nonLFV decay:

$$\begin{aligned} \tilde{\chi}_2^0 &\rightarrow \tau \tau \quad \tilde{\chi}_1^0 \rightarrow \mu \tau \nu_\mu \nu_\tau \quad \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 &\rightarrow \tau \tau \quad \tilde{\chi}_1^0 \rightarrow e \tau \nu_e \nu_\tau \quad \tilde{\chi}_1^0 \end{aligned}$$



$$E \equiv N(\mu^\pm \tau^\mp) - N(e^\pm \tau^\mp)$$

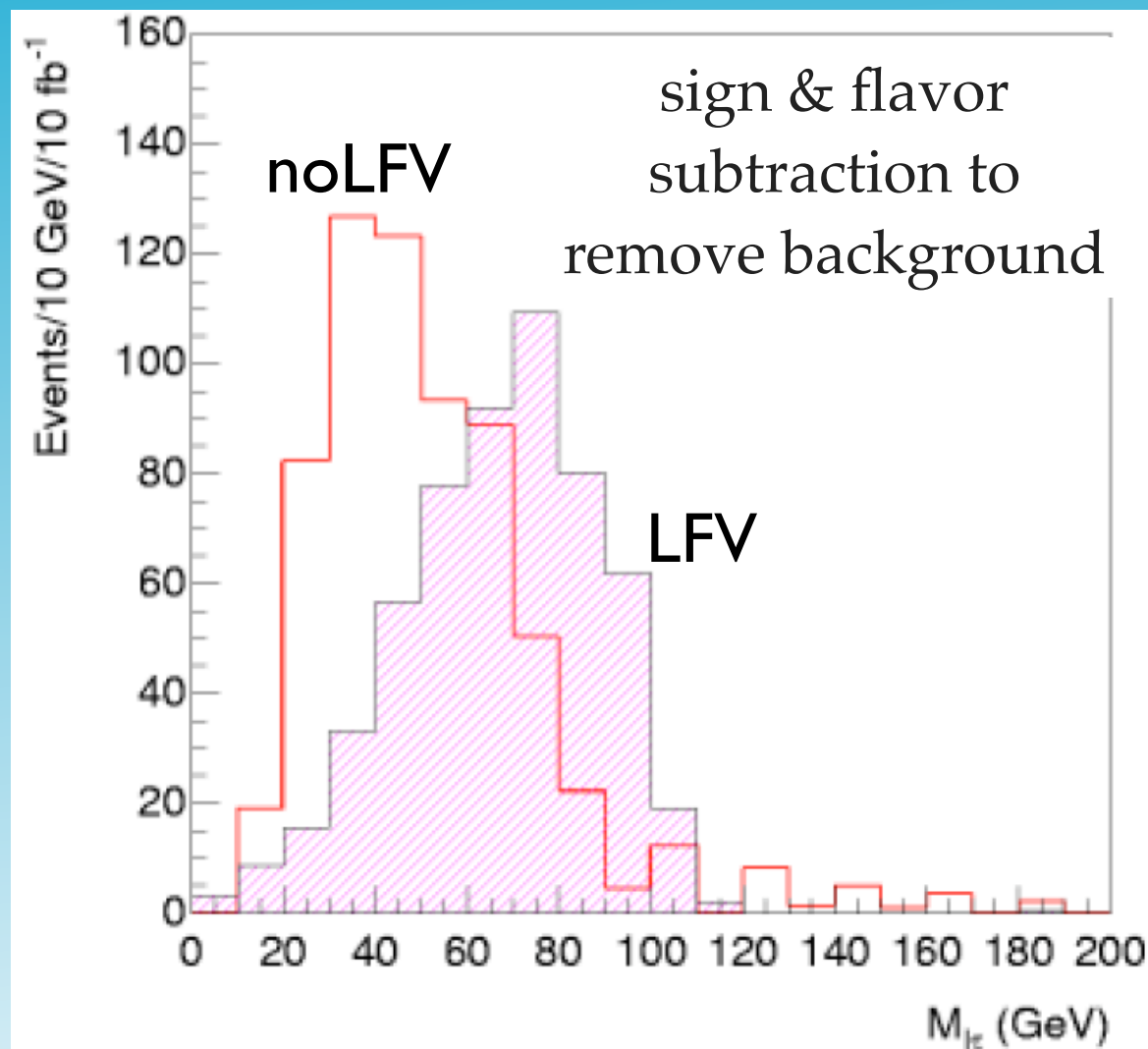
in case of nonLFV, expect  $E = 0$ .  
We can do a counting experiment.



For  $10\text{fb}^{-1}$  &  $\text{BR}=0.1 \rightarrow E = 476 \pm 39$ .

or if  $5\sigma$  signal is observed @  $10\text{fb}^{-1} \rightarrow \text{BR}=0.023$  or  $\delta \sim 0.1$

or  $\delta < 0.1 \rightarrow \text{BR} < 10^{-9}$





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# 2HDM -1

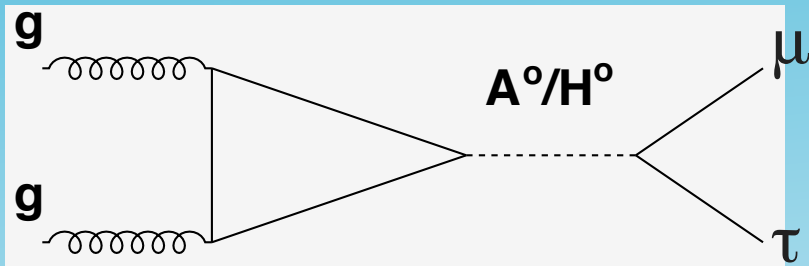
15

Phys. Rev. D 67, 035001 (2003)

Type III 2HDM: LFV exists @ tree level

$$\text{BR}(A^0/H^0 \rightarrow \tau\mu) = \kappa_{\tau,\mu}^2 \left( \frac{2m_\mu}{m_\tau} \right) \text{BR}_{SM}(H^0 \rightarrow \tau\tau)$$

$\kappa_{\mu\tau} \approx 1$  compatible w/  $\mu$  g-2 results



Considered Backgrounds:

$$W^\pm Z \rightarrow \mu^\pm \nu_\mu \tau^+ \tau^-$$

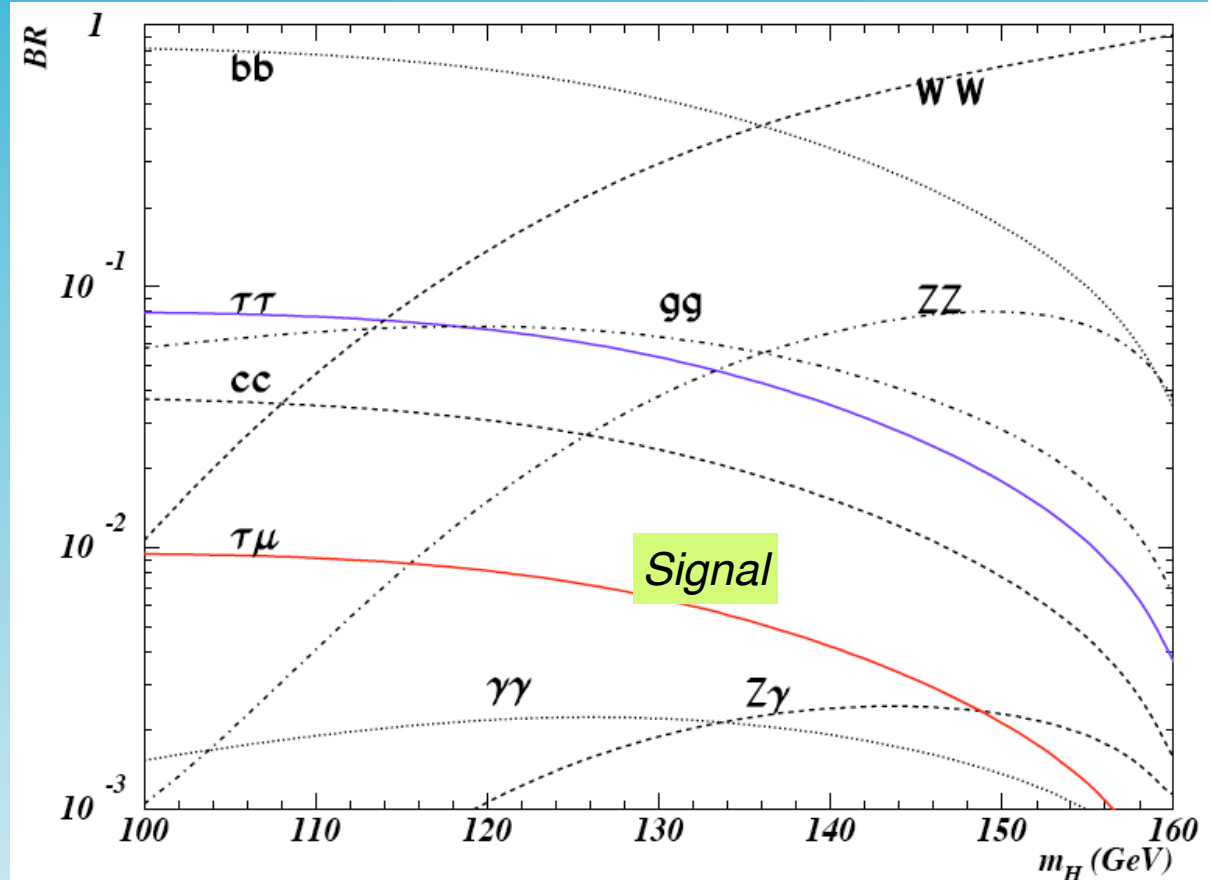
$$W^+ W^- \rightarrow \mu^+ \nu_\mu \tau^- \bar{\nu}_\tau$$

$$t\bar{t} \rightarrow \mu^\pm \nu_\mu \tau^\pm \nu_\tau b\bar{b}$$

$$Z(\gamma^*) \rightarrow \tau^+ \tau^- \rightarrow \mu \nu_\mu \nu_\tau \tau$$

$$W^\pm + \text{jets} \rightarrow \mu^\pm \nu_\mu + \text{jets}$$

→  $A^0/H^0 \rightarrow \tau^+ \tau^- \rightarrow \mu \nu_\mu \nu_\tau \tau$



Signal Final states:

- Hadronic final state:  
τ jet, isolated μ & missing E<sub>T</sub>
- Leptonic (e) final state:  
hadron activity, isolated e, μ & missing E<sub>T</sub>



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$\sigma_{bg}$  is  $10^4 \sigma_{signal}$

Cuts:

- 1 isolated  $\mu$ :  $p_T^\mu > 20$  GeV,  $|\eta^\mu| < 2.5$
- 1 hadronic  $\tau$ -jet:  $p_T^\tau > 20$  GeV,  $|\eta^\tau| < 2.5$
- b-jet veto and jet veto: 60% b-tagging, 1% mis-tagging efficiency.
- $\tau$ -jet ID efficiency of 30% assumed
- Signal efficiency:  $\sim 15\%$
- $W^\pm + \text{jet}$  background efficiency: 0.4%
- $Z^0 \rightarrow \tau\tau$ :  $\sim 3\%$

$$\frac{p_T^{\tau\text{-jet}}}{p_T^\tau} > 0.6,$$

$$\Delta R(p_T^{\tau\text{-jet}}, p_T^\tau) < 0.2 \text{ rad.}$$

Single charged track within  $\Delta R < 0.3$  of  $\tau$  jet

Selection of 1-prong hadronic  $\tau$  decays

$$\delta\phi(p_T^\mu, p_T^{\tau\text{-jet}}) > 2.75 \text{ rad,}$$

$$\delta\phi(p_T^{\text{miss}}, p_T^{\tau\text{-jet}}) < 0.6 \text{ rad.}$$

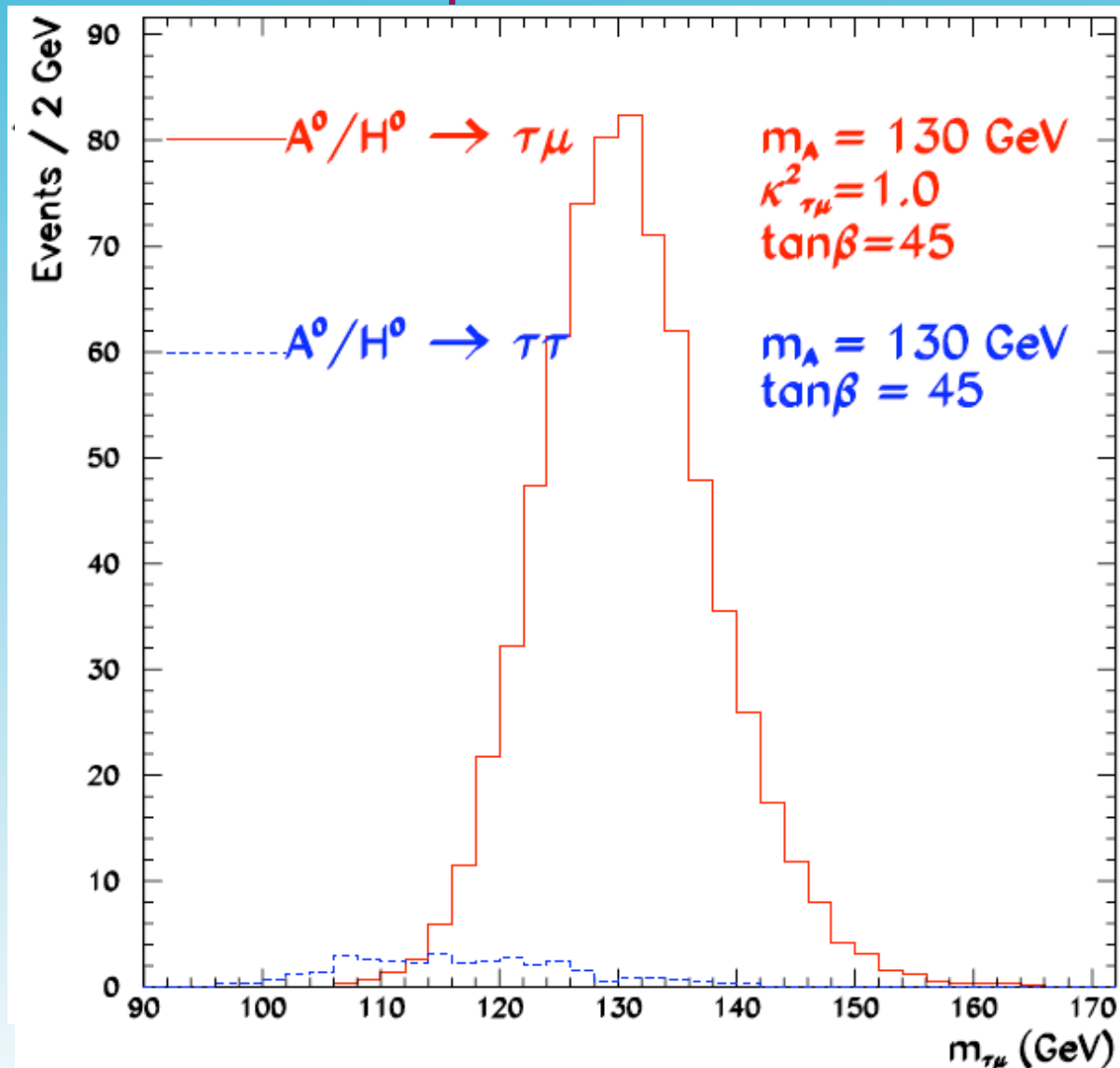
$$\Delta p_T = p_T^\mu - p_T^{\tau\text{-jet}} > 0 \quad p_T^\tau > 50 \text{ GeV}$$

# 2HDM -2

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Phys. Rev. D 67, 035001 (2003)

Pythia + ATLAS fast simulation,  $30 \text{ fb}^{-1}$   
Selection optimized for LFV mode:





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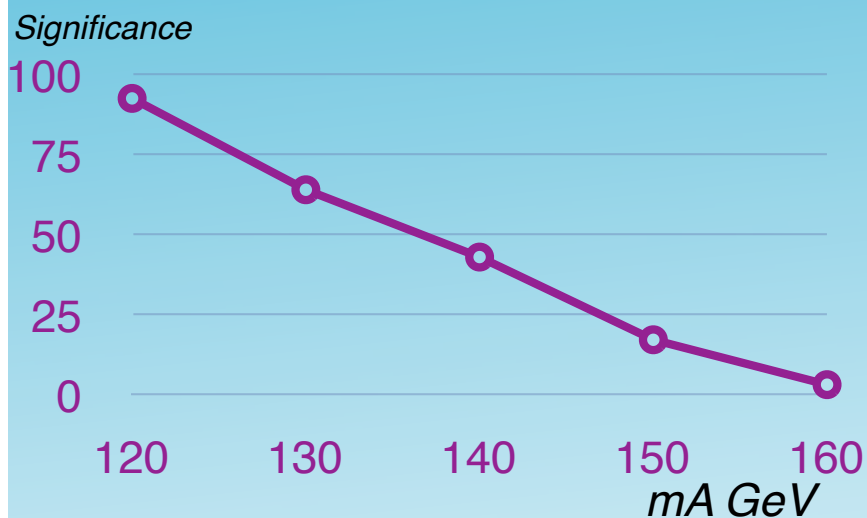
# 2HDM -3

17

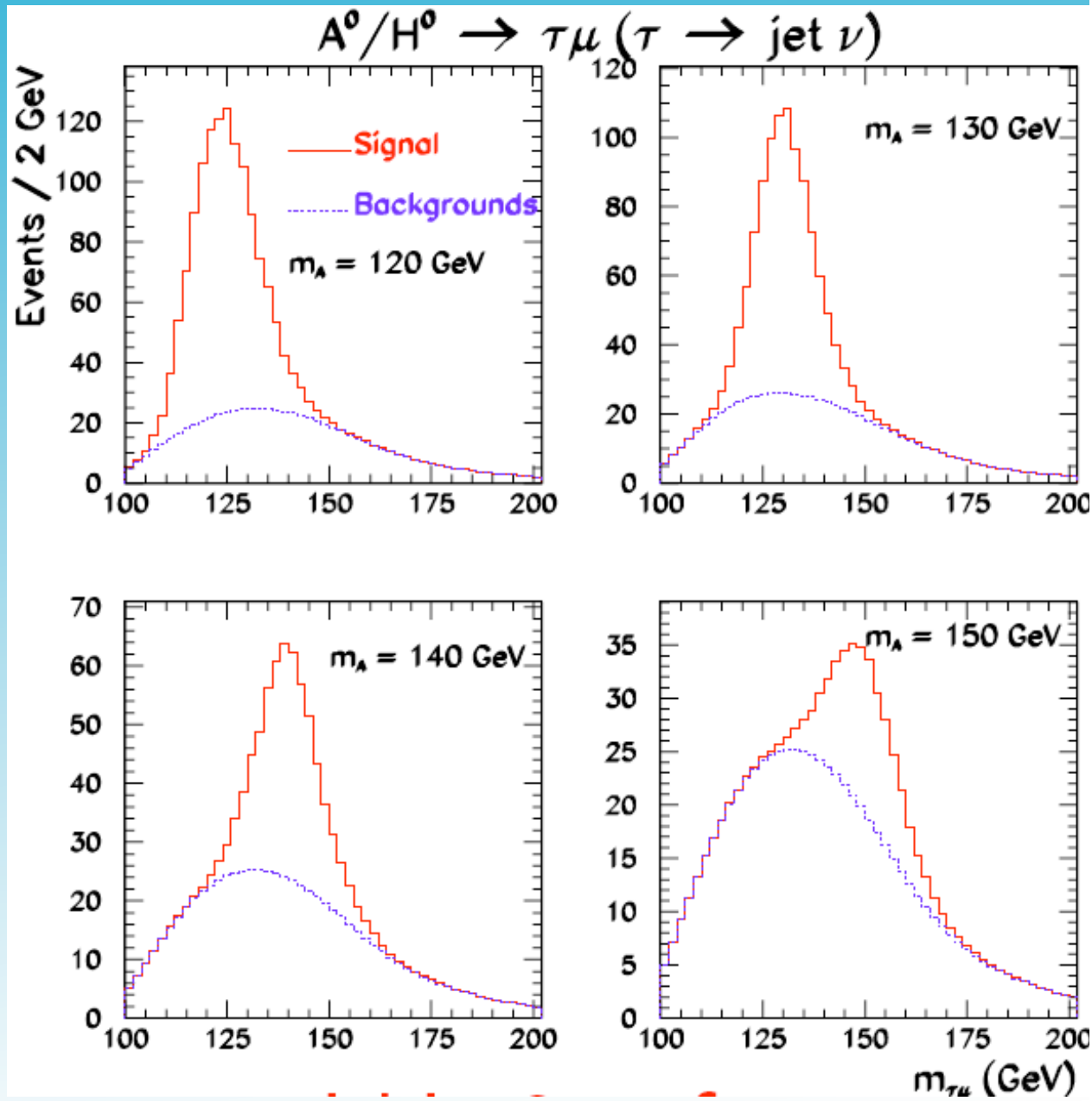
Phys. Rev. D 67, 035001 (2003)

signal is well in the reach of LHC/ATLAS:

MA(GeV)	120	130	140	150	160
s/ $\sqrt{B}$ combined	92.7	64.2	43.2	17.4	3.4



if signal, 95% CL can  
be obtained after few  
years of low luminosity





# LN<sub>V</sub> -1

- Doubly charged Higgs, single production
  - in Left Right symmetric models  $m_{WR} > 640 \text{ GeV}$
  - assuming equal left/right gauge couplings:  $g=0.64$
  - fast MC used @  $\mathcal{L}=100 \text{ fb}^{-1} / \text{yr}$

## Selection

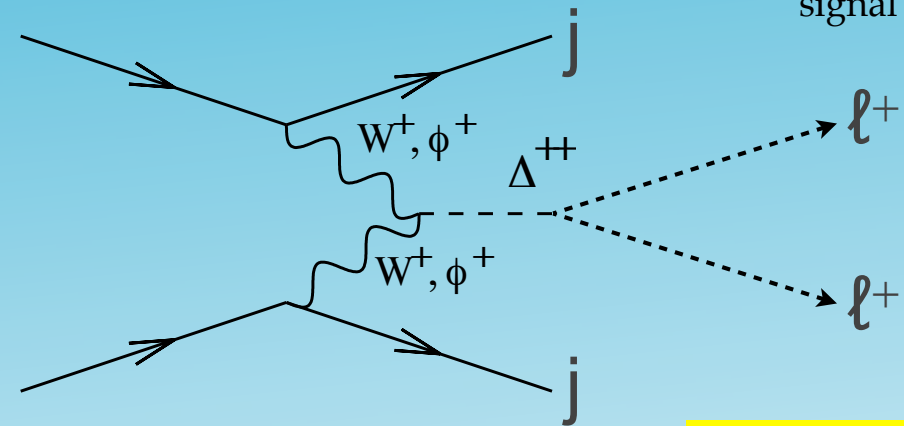
- $e/\mu$  in  $|\eta| < 2.5$  &  $\epsilon_{\text{reco}} = 90\%$
- $p_T^{\ell} > 50$  &  $p_T^{j1} > 200$  &  $p_T^{j2} > 200$
- $|\eta^{j1} - \eta^{j2}| > 2$

## SM Background

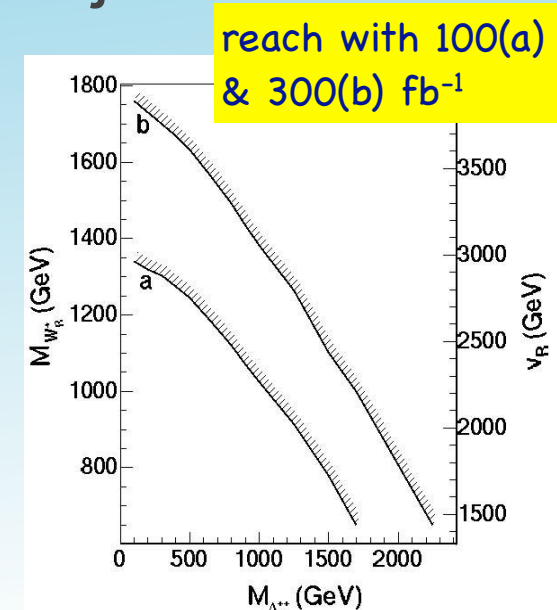
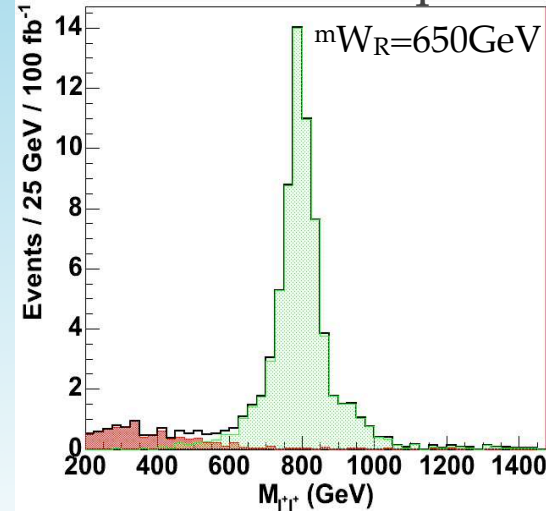
Background	Number of Events	$\sigma \times BR$ (fb)
$pp \rightarrow W t \bar{t}$	200 000	23
$qq \rightarrow W^+ W^+ qq$	100 000	37
$qq \rightarrow W Z qq$	27 000	28.6
$qq \rightarrow t \bar{t} \quad P_t \text{ 10-200 GeV}$	8 000 000	90 800
$qq \rightarrow t \bar{t} \quad P_t \text{ 200 GeV-}\infty$	2 000 000	14 100

$M(W_R^+)$	$M(\Delta_R^{++})$				
	300	500	800	1000	1500
650	7.9	4.6	2.2	1.4	0.45
750	4.7	2.8	1.4	0.87	0.31
850	2.9	1.8	0.90	0.58	0.21
950	1.9	1.2	0.61	0.40	0.15
1000	1.6	0.98	0.50	0.33	0.12
1050	1.3	0.81	0.42	0.28	0.11
1500	0.30	0.20	0.11	0.074	0.029

signal  $\sigma$  in fb



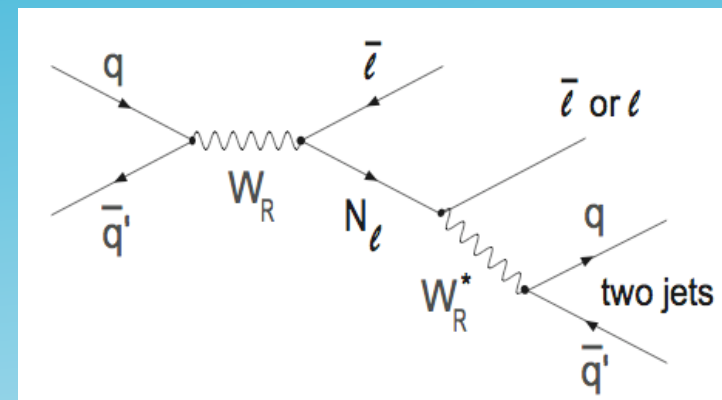
min 10 events required





## • LR symmetric model w/ $W_R$ & $N_{\text{majorana}}$

- Full MC used (14TeV)
- LO  $\sigma(pp \rightarrow W_R X); W_R \rightarrow \ell N_\ell \rightarrow \ell \ell jj$ 
  - 24.8pb ( $W_R=1800, N_\ell=N_\mu=300\text{GeV}$ ) (a)
  - 47.0pb ( $W_R=1500, N_\ell=N_\mu=500\text{GeV}$ ) (b)



## • Baseline Selection

- $p_T \geq 20 \text{ GeV}, |\eta^\ell| < 2.5, |\eta^j| < 4.5,$

## • SM Background

- $t\bar{t}, Z/\gamma^*$  & vector boson pair production + multijets for  $\ell=e$

Physics sample	Before selection	Baseline selection	$m_{ejj} \geq 100 \text{ GeV}$	$m_{eejj} \geq 1000 \text{ GeV}$	$m_{ee} \geq 300 \text{ GeV}$	$S_T \geq 700 \text{ GeV}$
(a)	0.248	0.0882	0.0882	0.0861	0.0828	0.0786
(b)	0.470	0.220	0.220	0.215	0.196	0.184
$Z/\gamma^*, m \geq 60 \text{ GeV}$	1808.	49.77	43.36	0.801	0.0132	0.0064
$t\bar{t}$	450.	3.23	3.13	0.215	0.0422	0.0165
VB pairs	60.9	0.610	0.522	0.0160	0.0016	0.0002
Multijet	$10^8$	20.51	19.67	0.0490	0.0444	0.0444

→ Lepton sign investigated after this publication.

discovery limits  
a:150pb<sup>-1</sup> & b:40pb<sup>-1</sup>



# Summary & Outlook

- ATLAS is currently running to record collision data
- LFV is studied within SM and via BSM
  - Yearly yields to discover LFV
    - susy:  $\text{exp } 476 \pm 39$  vs  $\text{bg } 0$
    - 2HDM:  $3.4 < S/\sqrt{B} < 93$
    - SM-like:  $\text{exp } 46 \pm 2$  vs  $\text{bg } 1$
  - or push  $\text{BR}(\tau \rightarrow \mu \gamma)$  limit to lower values
- LNV studied in BSM models
  - $\Delta^{++}$  mass up to 1.8TeV depending on  $W^+$  mass
  - Early discovery possible in LR models, but SS vs OS lepton comparisons not public.
- Some of these analyses shown can be also done with 200  $\text{pb}^{-1}$  at  $\sqrt{s}=10\text{TeV}$  (the results are not yet public)

## • Further references

### • Neutrino oscillation papers

- K2K: hep-ex/0411038, Phys.Rev.Lett.94:081802,2005
- Kamland: hep-ex/0406035, Phys.Rev.Lett.94:081801,2005  
arXiv:0801.4589 Phys.Rev.Lett.100:221803,2008

### • Current LFV limits (thanks to S. Banerjee)

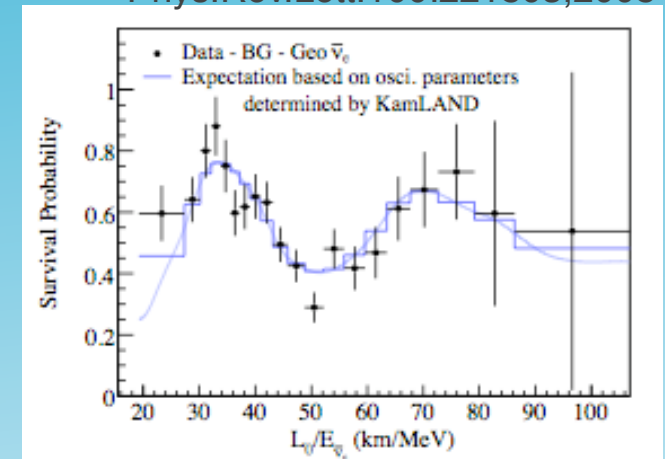
- BaBar: arXiv:0908.2381 (2009),  $\text{BR}(\tau^\pm \rightarrow \mu^\pm \gamma) < 4.4 \times 10^{-8} @ 90\% \text{ CL}$
- Belle: arXiv:0708.3272 (2007),  $\text{BR}(\tau^\pm \rightarrow \mu^\mp \mu^\pm \mu^\pm) < 3.2 \times 10^{-8} @ 90\% \text{ CL}$

### • J.Ellis et.al. Eur. Phys. J. C14, 319, (2000).

## • ATLAS public web pages :

- <http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>
- <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EXOTICS>

Phys.Rev.Lett.100:221803,2008





$$\tau \rightarrow \mu \gamma$$

E. Barberio  
unpublished

Source:  $Z \rightarrow \tau \tau$

*Pythia + Photos + Atlas Fast simulation was used.*

Compared to W channel, 10x less signal  
1 tau for tagging, other for signal

*generator cuts:*

$$\begin{aligned} \cos \theta_{||} &< 0.5 (M_Z) \\ P_{T\text{miss}} &< 60 \text{ GeV} \\ N_{\text{jet}} &< 2 \\ 0.5 &< m(\tau \gamma) < 3.0 \text{ GeV} \end{aligned}$$

*analysis cuts:*

$$\begin{aligned} p_T^\mu &> 6 \text{ GeV} \\ E_T^\mu(e, \gamma) &> 15 \text{ GeV} \end{aligned}$$

selection efficiency ~14%

Studied Backgrounds:

$$W \rightarrow \mu \nu \gamma$$

$$W \rightarrow \tau \nu \gamma$$

$$\tau \rightarrow \mu \nu_\mu \nu_\tau$$

$$Z \rightarrow \mu^+ \mu^- \gamma$$

$$Z \rightarrow \tau^+ \tau^- \gamma$$

$$\tau \rightarrow \mu \nu_\mu \nu_\tau$$

$$t \bar{t} \gamma$$

$$b \bar{b} \gamma$$

low luminosity

$$1.6 < M < 2.0 \text{ GeV}$$

~12 bg events/year for  $m_\tau$

~10 signal events/year



# ATLAS & CMS detectors

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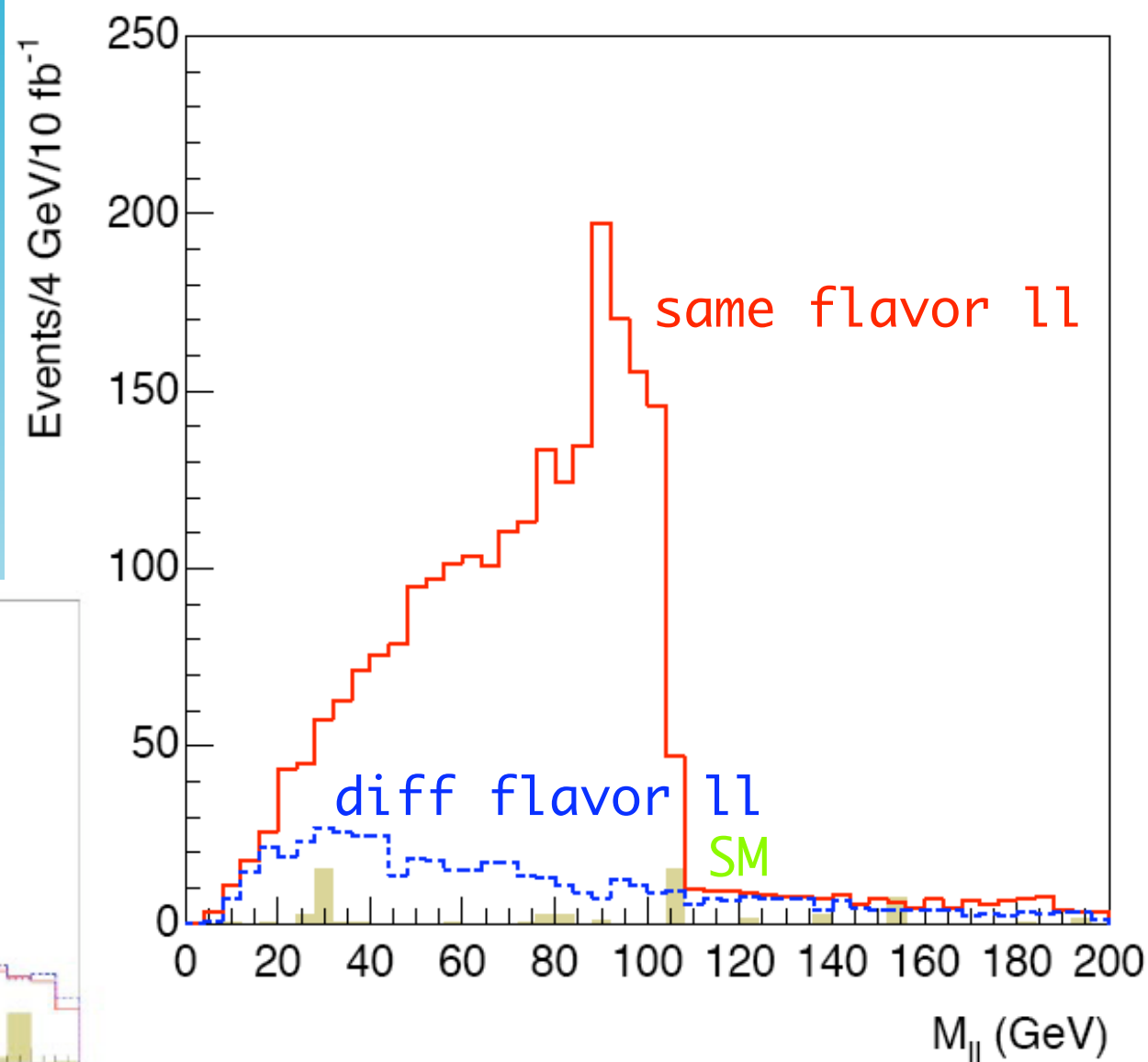
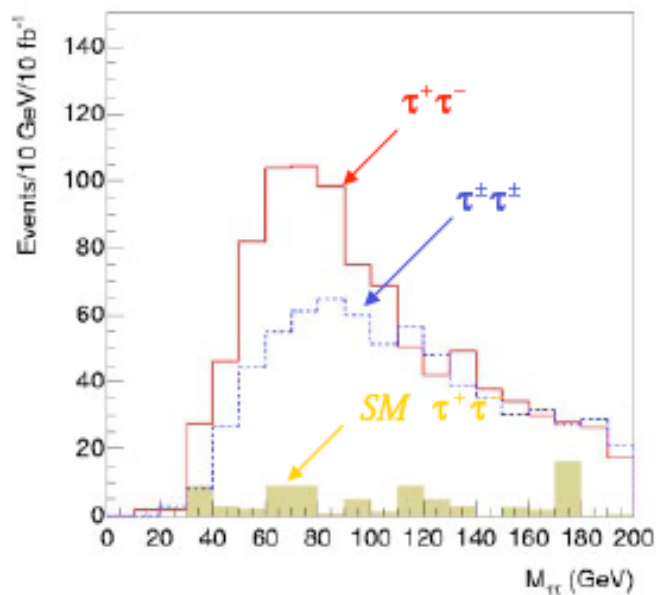
	ATLAS	CMS
length x diameter (m)	44 x 22	22 x 15
Magnetic Field (Tesla)	2	4
Weight (Tons)	7 000	12 500
eta coverage	2.7>muons, 2.5>tracking 4.9>calo	2.4>muons, 2.5>tracking 5.0>calo
Inner detector	Silicon pixels, Silicon strips, Transition Radiation Tracker.	Silicon pixels, Silicon strips.
Electromagnetic Calo	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ( $\text{PbWO}_4$ ) crystals both absorb and respond by scintillation
Hadronic Calo	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon System	Large air-core toroid magnets with muon chamber form outer part of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke



□  $\tau\tau$

Background  
dominated by

$$\tilde{\chi}_1^\pm \rightarrow \tau^\pm \tilde{\chi}^0$$

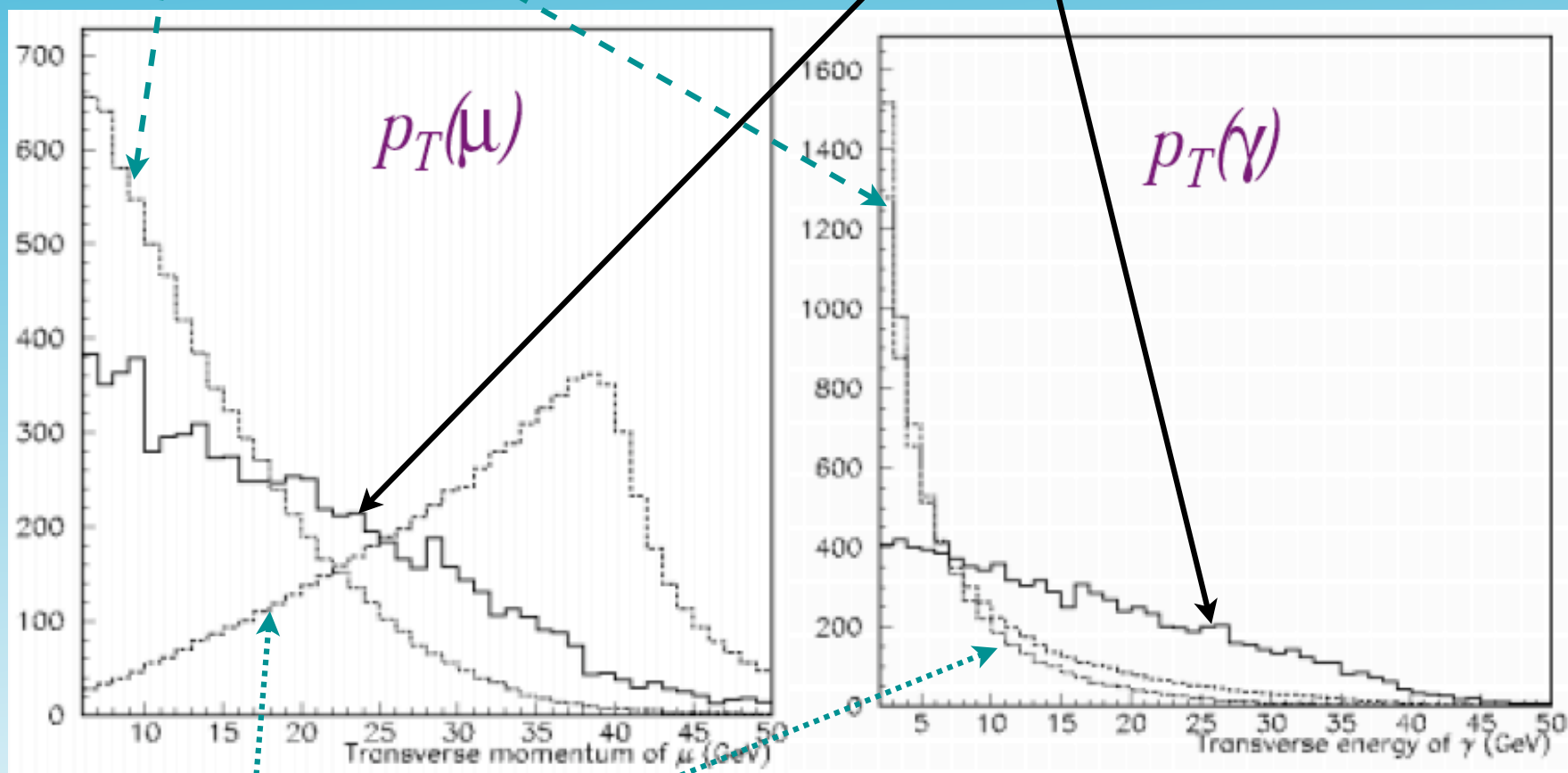


# $\tau \rightarrow \mu \gamma$ details

kinematic distributions

$$W \rightarrow \mu \nu_{\mu} \gamma$$

$$\tau \rightarrow \mu \gamma$$



$$W \rightarrow \tau \nu_{\tau} \rightarrow \mu \nu_{\mu} \nu_{\tau} \gamma$$